Detecting cracked shafts at earlier levels

By Don Bently

Cracked shafts are most commonly detected by non-touching shaft probes observing excessive vibration at rotative speed, according to documented data. Yet, the cracks have not been detected as early as they could be if two methods were used. This column discusses these methods.

Documents on the saves of cracked shafts reveal the shaft radial vibration level increased slowly at first and rapidly in the final stages. One documented case noted an increase of 1 peak-to-peak mil per hour. These saves showed lateral cracks of 60 percent depth-to-diameter ratio.

It is excellent that these saves are occuring, but it is very desirable to know that a crack exists sooner than the 60 percent figure.

There are two solid means of detecting cracks at earlier levels. The first method is online documentation consisting of the normal variations of amplitude and phase vectors of radial vibration. The second method is the recording and subsequent data reduction of radial vibration on startups, coastdowns, and heat spin tests of turbines and generators.

All known tests currently used to detect cracks, such as ultrasonic, Zyglow, Magnaflux, and visual inspection, etc., should be continued. These tests are in addition to the methods we are discussing today, but do not involve disassembly of the machine train.

Online Crack Detection

This method involves plotting each shaft displacement motion point monitored: vertical and horizontal shaft displacement (shaft displacement with respect to the housing, and shaft displacement with respect to the free space, i.e. dual probe, if available). Make a polar plot history of the rotative displacement motion vector as a function of time, as well as of megawatts, horse-

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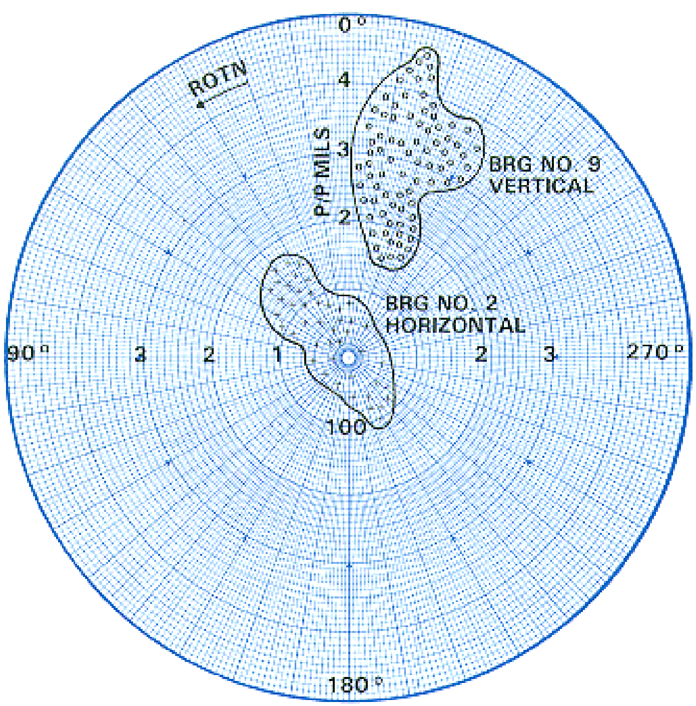

Figure 1: Typical "shotgun" patterns of rotative motion vectors

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Bently's Corner

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power, field current, steam condition, or other factors which influence the shaft rotative speed response vector.

Plotted over a period of time and load, a "shotgun pattern" of the normal rotative speed vibration vector distribution will be established. Typical polar plot histories are shown in *Figures 1* and *2*.

In the historical polar plot of each bearing, a lateral crack will appear as a shaft bow. The shaft bow, in turn, will exhibit a vector pattern outside this range.

This online crack detection method should yield reliable indication of a crack much earlier than the 60 percent range at which machines are currently shut down. Cracks in the order of 40 percent may be spotted using this historical sampling technique. Surely the indication will be much earlier and, therefore, better than shutdown on gross vibration level.

In making this measurement, the machine train must be equipped with at least vertical and horizontal shaft relative displacement probes at each bearing, and ideally with dual probes to measure shaft absolute displacement as well. A Bently Nevada vector filter is required to resolve the rotative speed (1X) component of each displacement motion. This can be accomplished by using a Bently Nevada Smart Monitor®, a Bently Nevada Turbine Supervisory Instrumentation system with a Digital Vector Filter installed in the monitor rack (DVF-R), or with a Bently Nevada vector filter multiple (VF-M).

Portable instruments, such as the Digital Vector Filter 2 (DVF 2) or TK-20, may also be utilized to measure rotational speed vectors. The historical polar plot for each radial displacement vibration probe can be posted by hand or by a Bently Nevada Smart Monitor Host Processor.

The results should be periodically monitored by the responsible production management as well as by the responsible equipment engineer. Readings outside the historical pattern should cause major concern.

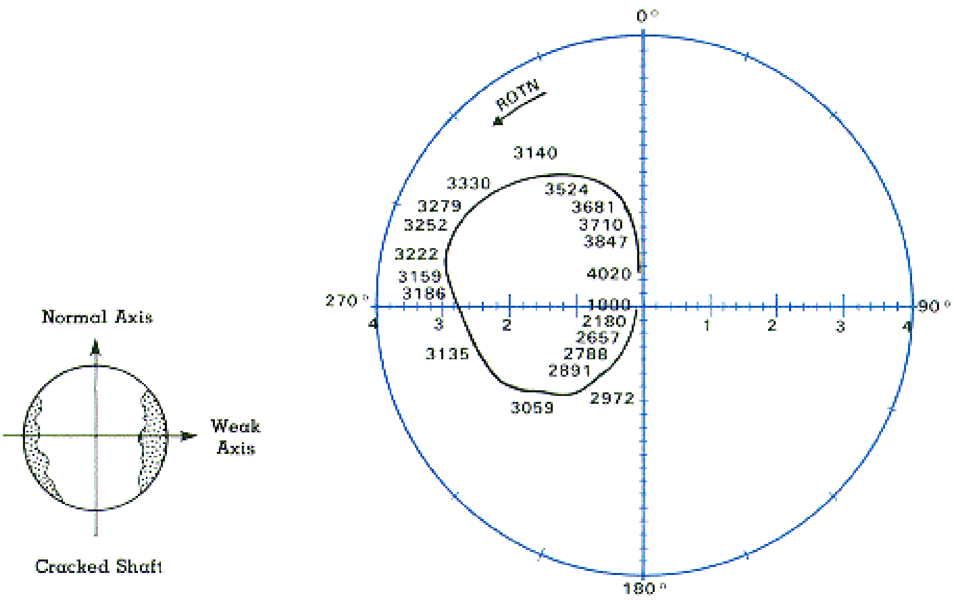

Figure 2: 2X response of cracked shaft (sawcut 20% of diameter)

A typical graph of the expected behavior of the twice rotative speed vibration vector is shown in *Figure 2*.

Startup and Shutdown Vibration Recording, and 2X Data Reduction

In the early history of rotor mechanics, the behavior of an asymmetric shaft was observed. Over a long period of years, more than 50 papers have appeared on this subject. It is well known that a lateral crack produces asymmetric spring restraint and that if the rotor is loaded by a soft preload, such as a horizontal machine with soft gravity preload, the rotor responds to this twice per turn reaction of gravity by producing a special Mathieu equation effect generally called the "gravity critical."

An excellent paper from the United Kingdom about 15 years ago noted this "gravity critical" as a method of detecting a crack. Another important work has been recently published by Kanki, Shiraki, and Inagaki (Mitsubishi), entitled "Transverse Vibration of a General Cracked-Rotor Bearing System" (ASME 81DET-45). This work is a reaffirmation of the "gravity critical" technique using the latest diagnostic tools produced by Bently Nevada.

Three steps are required to perform this second method of crack detection. First, during each startup and shutdown of the machine train, use a FM tape recorder or an equivalent digital system to document the Keyphasor signal and the radial shaft displacement signals, both vertical and horizontal if possible, to determine the shaft relative displacement and the shaft absolute displacement, if available.

Then document the rpm region of the first self-balance resonance speed (first critical) of the span each transducer is observing. (Documentation of the second self-balance resonance speed may also be useful.)

Finally, using a Bently Nevada ADRE® system, set the Bently Nevada Digital Vector Filter for 2X and study each radial vibration channel in the rpm range of 40-60 percent of the documented self-balance resonance. (For example, if the first self-balance resonance is 1500 rpm, run 2X rotative speed response in the region of 600-900 rpm.)

If the shaft is asymmetric due to a crack, a vertical and horizontal polar plot of the 2X rotative speed "gravity critical" response will be observed. Be sure that a foundation or piping resonance of the rotor system is *not* in this same rpm range by observing the casing response along the machine train. The best data will probably be obtained during coastdown due to the absence of cold thermal bows and "hot" running alignment. (continued next page, col. 1)

This 2X "gravity critical" should be plotted in polar form. With the normal damping of a rotor system, lateral cracks of as little as 10 percent depth-to-diameter ratio are readily detected. This is at a much earlier crack stage than other assembled tests can accomplish.

Three warnings regarding the second method are pertinent. First, a crack at a purely vertical shear point (no bending moment) may not be observed by either method.

Second, this method is very sensitive to damping. Either a large crack or poor damping may cause complete rotor destruction at "gravity critical" and/or at first self-balance resonance speed. Use shaft bow limit clearance bearings at the center of the rotor to ensure safety during spin pit tests. (During startup or shut down of the machine, the internal seals usually act as vibration limiting devices.)

Third, there is some cross coupling of 1X motion (due to unbalance) to the size and orientation of the 2X polar plot. Good trim balance is desirable for best results.

Summary

It is strongly recommended that the online polar plotting method of the 1X radial displacement motion vector history be instituted. This makes it possible to see deviations in the unbalance of the rotor system which may be caused by a propagating lateral shaft crack.

We also recommend that all startups and shutdowns be tape recorded for subsequent diagnostic review for 2X polar plot "gravity critical" behavior. Of course, review any available tape recordings previously taken of your rotating machinery for this mechanism. (Note that this test does not apply to vertical machines unless some other soft preload replaces the lateral effect of gravity.)

As compared to other categories of machine malfunctions, cracked shafts are very rare. A broken shaft, however, can be just as dangerous as a fire in an oxygen machine. Any machine with a suspected cracked shaft should be shut down and operated only under dire emergency production conditions.

Dr. Agnes Muszynska will present a paper on this subject in October at the National Research Council of Canada conference in Edmonton. The paper provides new insights into the behavior and detection of cracked shafts.

PRODUCT LITERATURE

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